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Hydrogen economy in China: Strengths–weaknesses–opportunities–threats analysis and strategies prioritization

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ABSTRACT

The objective of this paper is to analyze the internal and external environment of hydrogen economy in China using strengths–weaknesses–opportunities–threats (SWOT) analytical method, and then to prioritize the strategies for promoting the development of hydrogen economy in China. After the key strengths, weaknesses, opportunities and threats of the hydrogen economy in China were identified and nine effective strategies were proposed, a multi-criteria decision-making method by integrating goal programming and fuzzy theory has been developed for prioritizing these strategies, which can help the stakeholders/decision-makers to implement these strategies appropriately, The proposed method is not limited to China, and it is a generic method that can also be used to study the hydrogen economy of other regions.

Contents

1. Introduction

Hydrogen is widely regarded as a promising energy carrier for decarbonizing road transport, mitigating the emission of harmful gases, and enhancing the security of energy supply, accordingly, hydrogen economy has attracted more and more attention around the world recently [1–3]. A variety of governments have published technology roadmaps of hydrogen economy, according to which,

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the scientists and engineers can closely monitor the scheduled progress of hydrogen technologies [4–7].

Hydrogen economy refers to a proposed system, in which, hydrogen is produced from carbon dioxide-free sources and is used as an alternative fuel for transport [8]. As the largest energy consumer in the world with a coal-dominated energy structure, China is also attempting to make a transition to hydrogen economy for a more sustainable future [9–15]. While an essential prerequisite for a successful transition is to accurately evaluate the current status of hydrogen economy in China and draw effective strategies for promoting its development, the objective of this study is to identify the key characteristics of hydrogen economy in China and provide strategies for promoting its development.

In the study, strengths–weaknesses–opportunities–threats (SWOT) analytical method is used to analyze the strengths, weaknesses, opportunities and threats of the hydrogen economy in China. Subsequently, the strategies for promoting its development were proposed by exerting strengths, mitigating weaknesses, exploiting opportunities and avoiding threats. While the SWOT method does not provide an analytical way to quantify the effectiveness and to prioritize these strategies according to their importance, a multi-criteria decision-making (MCDM) method has been developed to rank the prior sequence of the strategies. By combining the MCDM and SWOT methods, the stakeholders/decision-makers can make correct decisions by giving top priority to these strategies that have significant effect on the development of hydrogen economy in China.

The remainder of this paper is structured as follows: Section 2 presents the SWOT analysis method and its application in analyzing the hydrogen economy in China. In Section 3, the developed MCDM method was described and used to prioritize the strategies for promoting the development of hydrogen economy in China. Finally, the study was concluded in Section 4.

2. SWOT analysis of hydrogen economy in China

2.1. SWOT method

Strengths–weaknesses–opportunities–threats (SWOT) analytical method is widely used for strategy formulation by constituting an important basis for learning about the situation of the studied object and for designing future strategies to solve the existing problems [16–18]. SWOT analytical method can identify the strengths (elements to leverage and build on), weaknesses (areas to seek assistance and support), opportunities (areas to leverage for the advantages) and threats (elements to hinder the development of the object) of the studied objects [19]. The strengths and weaknesses are determined by the internal factors, whereas external forces dictate opportunities and threats [20]. SWOT analytical method has been successfully used in the energy fields such as the analyses of sustainable energy development [21], electricity supply chain [22], regional energy planning [23], the development of shale gas [24] and bioenergy [25].

When SWOT method was used to analyze the hydrogen economy in China, the internal and external forces which might affect the development of hydrogen economy in China are first collected and summarized according to a questionnaire survey by providing the regulations, reports, literatures, papers, documents, legislation, statistics and the data concerning the research topic to the participants, and then further determined by the experts in a way of brainstorm. Its framework consists of 5 steps (Fig. 1).

Step 1: Materials collection. The purpose of this step is to collect the related data and materials concerning the research topic, the supplementary materials such as regulations, reports, literatures, papers, documents, legislations, and national statistics are all gathered.

Step 2: Questionnaire design and survey. The main questions in the questionnaire should be developed with the help and under the supervision of the senior experts in this area. The objective of these questions is to identify the strengths, weaknesses, opportunities and threats of the studied objects. The designed questionnaire will be assigned to a number of stakeholders and experts concerning the research topic, and they are asked to fill the questionnaire based on their own experience and the provided materials.

Step 3: Brainstorm. The purpose of this step is to organize a colloquium to determine the factors regarding strengths, weaknesses, opportunities and threats, and to recommend strategies for improving the status of the studied objects. In the colloquium, many experts concerning the research topic will be invited to analyze the questionnaires responded by the stakeholders in step 2.

Step 4: SWOT analysis. According to the obtained results in the colloquium, all the factors regarding strengths, weaknesses, opportunities and threats are discussed, analyzed and specified by using the SWOT analytical method in this step.

Step 5: Strategy recommendations. According to the factors regarding the strengths, weaknesses, opportunities and threats, effective strategies to fully use the strengths and opportunities, and avoid or mitigate the weaknesses and threats are determined in the brainstorm. Afterwards, SWOT matrix [26] is used to identify four types of strategies, i.e. strengths–opportunities (*SO*) strategies, weaknesses–opportunities (*WO*) strategies, strengths–threats (*ST*) strategies and weaknesses–threats (*WT*) strategies, as showed in Fig. 2. Specifically, *SO* strategies are obtained by matching internal strengths with external opportunities and using strengths to take advantages of opportunities; *WO* strategies are obtained by matching internal weaknesses with external opportunities and overcoming the weaknesses by taking advantages of opportunities; *ST* strategies are obtained by matching internal strengths with external threats and using strengths to avoid threats; *WT* strategies are obtained by matching internal weaknesses with external threats and minimizing weaknesses to avoid threats.

2.2. Application of SWOT method in analyzing hydrogen economy in China

SWOT analysis can help stakeholders/decision-makers to better understand the current status of hydrogen economy in China, and then draft strategic plans to promote its development. According to the framework of SWOT method, the procedures for analyzing hydrogen economy in China can be specified as the followed steps.

Step 1—Material collection. In this step, the books, patents, reports, documents, legislation, statistics relating to the hydrogen economy in China, as well as the related papers in China National Knowledge Infrastructure and Science Direct were collected.

Step 2—Questionnaire design and Survey. The questionnaire for identifying the strengths, weaknesses, opportunities and threats of hydrogen economy in China was designed in Mandarin (the English version has been presented in the Appendix) [27].

The survey has been conducted by assigning the questionnaire to a total of 80 experts through emails and interviews during June to August in 2013, including 20 professors whose expertise are in the areas of hydrogen energy or other renewable energy sources from Chinese universities; 20 administrative

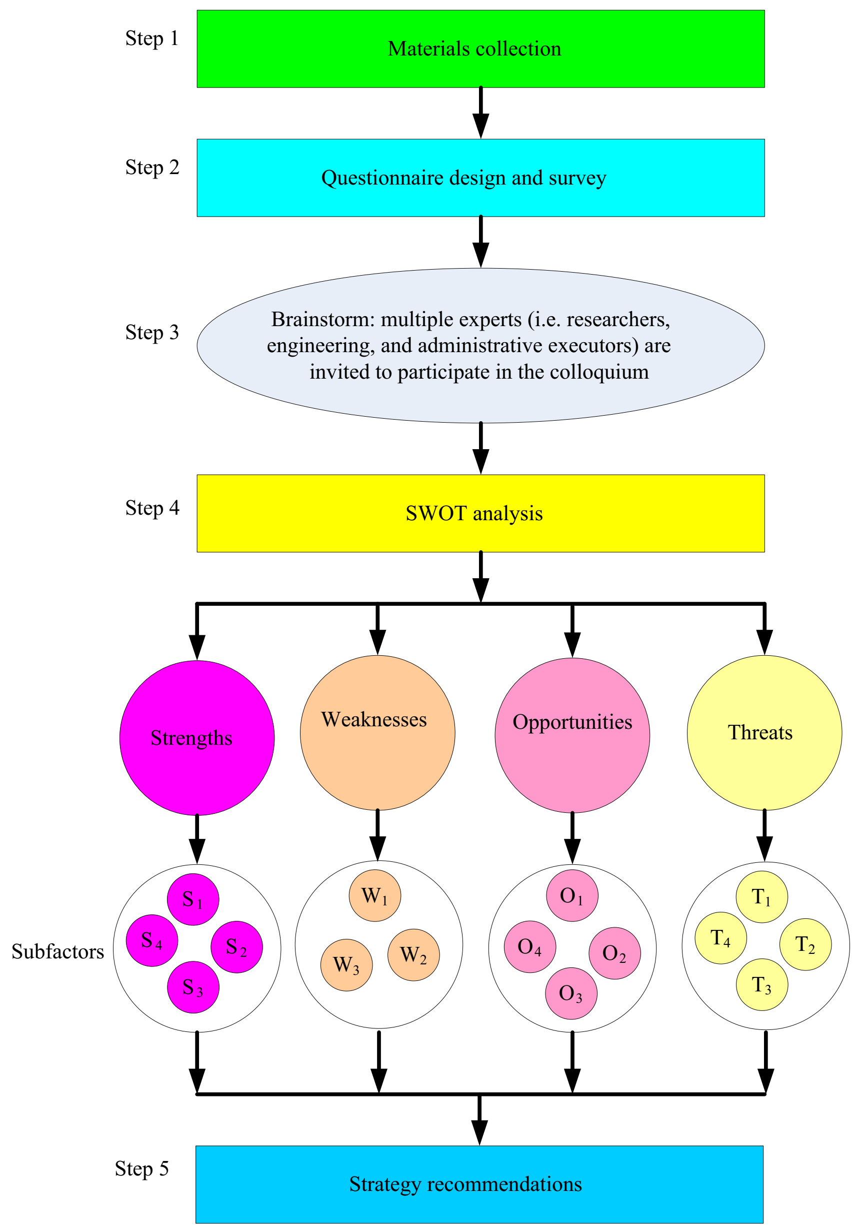

Fig. 1. The framework of SWOT method.

executors from different government sectors, e.g. the local Development and Reform Commission and the local Environment Protection Bureau; 20 engineers from renewable energy companies, chemical plants, and chemical engineering design institutes; and 20 Ph.D students whose research areas are hydrogen energy, energy planning, or some other renewable energy sources. At the end the survey, a total of 67 responses were received including 17 professors, 13 administrative executors, 17 engineers, and 20 students.

Step 3—Brainstorm. In order to understand the status of hydrogen economy in China comprehensively, the representative experts including 3 professor from Chongqing University, 2 administrative executors from the affiliated sectors of Chongqing Municipal People's Government, 3 engineers specialized in fuel cell vehicles and hydrogen technologies, 2 Ph.D students of hydrogen energy, were invited to participate in the colloquium, and a coordinator was nominated. The results of the questionnaire survey processed and arranged by the authors were provided to the participants in the colloquium. Afterwards, Delphi method was used to determine the final characteristics (strengths, weaknesses, opportunities and threats) of the hydrogen economy in China, and also the strategies for promoting its development as Delphi method has the characteristics of anonymity, feedback and convergence. Anonymity means that the experts fill the questionnaire independently, and this characteristic of the Delphi method is helpful to draw on the wisdom of the masses. Feedback means that the Delphi method emphasizes the communication and feedback of information. Each round of evaluation would collect and collate all sorts of opinions and materials of the preceding round. These opinions and materials would be delivered to experts along with the questionnaire, which helps experts to fully understand every kind of objective situation and points of view of other experts, and thus improves the comprehensiveness and reliability of the evaluation process. Convergence means that the method can avoid the subjective and one-sidedness of a single survey through several rounds of evaluation, during which various opinions are compared,

Fig. 2. SWOT matrix.

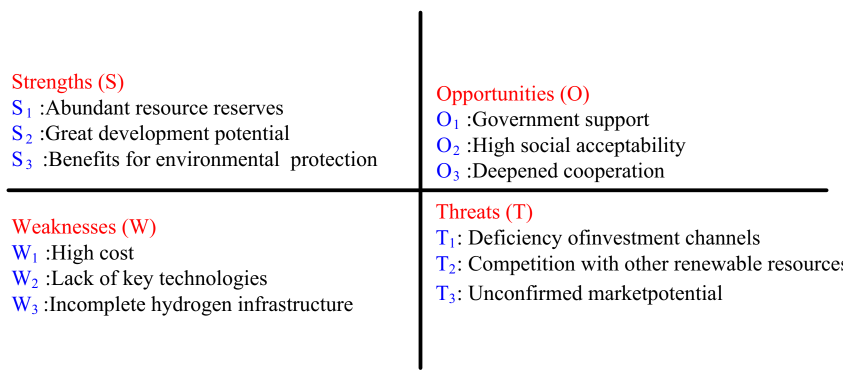

Fig. 3. Key SWOT factors for hydrogen economy of China.

verified and convinced. Eventually, the scattered opinions were gradually converged to the correct one [28]. During the colloquium, for the debates that the participants have different opinions, a final consensus was usually achieved by the rule of "the minority is subordinate to the majority".

Step 4—SWOT analysis. After the colloquium, the factors regarding strengths, weaknesses, opportunities and threats are indentified (Fig. 3).

- Strengths

  The factors regarded to be the strengths of the hydrogen economy in China include abundant resource reserves (S_1), great development potential (S_2), and benefits for environmental protection (S_3).

(1) Abundant resource reserves

Hydrogen as a clean energy carrier can be produced from a variety of sources, e.g. coal, oil, natural gas, biomass, waste water [29,30]. Moreover, Hydrogen can also be produced form abundant renewable resources e.g. hydro power, wind power, and solar power. The estimated amount of the renewable energy resources in China is approximates 7.2 billion tones coal equivalent [31].

Wind. China is rich of wind resources in the north, from Xinjiang Autonomous Region through Gansu Province to Inner Mongolia Autonomous Region, and in the southeast, along the coastline, and the total available wind energy is about 3.2 TW [32]. China had been the world's second largest wind producer since 2011, generating 73 TW h electricity, and China's installed on-grid wind capacity reached 61 GW in 2012 [33]. According to the Medium and Long-term Development Plan for Renewable Energy, the total capacity could amount to 150 GW by 2020 with an annual increase rate of 22.5% [34,35].

Hydro. The hydropower resources in China are concentrated in Yangtze, Lancang and Yellow Rivers as well as their tributaries [36,37]. Hydropower plays an important role in China's electric industry, the installed capacity of hydropower reached 14,823 million kW at the end of 2007 [38]. At the end of 2008, the installed capacity of hydropower in China, the largest in the world, accounted for 21.6% and 16.4% of national installed electricity capacity and annual electricity generation, respectively [36,37]. According to the recent report of International Energy Agency (IEA) and U.S. Energy Information Administration (EIA), the gross hydro-based electricity was 698,945 GW h in 2011 [39], the installed hydroelectric generating capacity was 249 GW in 2012 [33], and expected to continuously increase rapidly [40].

Biomass. As a large agricultural country, the biomass resource in China is equivalent to 890 million tons of standard coal resource annually [36,37,41]. Moreover, more and more attentions have been paid to biomass power by the Chinese administrations, The Law of Renewable Energy with a series of preferential policies related to biomass power have been issued to promote the development of biomass power [42,43]. In 2011, the total installed biomass power capacity in China was more than 8 GW, and also expected to increase

significantly [33]. The goal of biomass power generation drafted by Chinese Central People's Government is to achieve 30 GW of installed capacity in 2020 [44]. Besides using biomass power for hydrogen production, biomass is also one of the most promising feedstocks for hydrogen production in China, the estimated hydrogen supply potential from forest residues and that from agricultural residues is around 2.01×10^{11} N m^3 and 2.79×10^{11} N m^3, respectively [45].

Solar. There is a great potential for solar power in China, because many regions of China, such as Tibet, Qinghai, Xinjiang, Gansu can produce vast supplies of solar energy [36]. The development of solar in China used to be slow before 2004, but has speeded up during the past 10 years. In 2007, the total yield of solar energy in China was 1088 MW [46], and in 2011, the gross electricity generated by solar thermal and solar photovoltaic systems reached 1 GW h and 2532 GW h in 2011, respectively [39].

Geothermal power. The geothermal energy in China is mainly reserved at the circum-pacific tropical and Himalaya-Mediterranean tropical zone. Around China, more than 3200 thermal spots have been found, and the most famous geothermal power plant is Yangbajing geothermal power station located in Tibet, the gross electricity generated by which reached 153 GW h in 2011 [39,41,46,47].

Ocean energy. Ocean energy resources include tidal energy, wave energy, oceanic flow energy, temperature difference energy and salt difference energy, however, only the tidal energy can be actually utilized at present [46]. China's available ocean energy was mostly reversed in South China Sea. It has been estimated that about 1.1×10^{11} W of tidal energy can be exploited [46,48].

Besides, nuclear energy is also a promising power for hydrogen production in China [49–51]. Therefore, it can be concluded that there are abundant resources in China for hydrogen economy.

(2) Great development potential

China is unique for its vast country, large population and rapid economic growth [29,52]. With the rapid development, a large amount of energy is needed for the economic and social development [53–55] and China has become the world's largest energy consumer and emitter of greenhouse gases. Accordingly, China has paid more and more attention on developing renewable energies [56]. On the other hand, transport and communication is the fastest-growing energy consumer in China. It is reported that the on-the-road vehicles in China has increased by nearly fifty-fold from 1.36 million units to 70 million units during the last three decades [57], and the development of hydrogen and fuel cell vehicles is one of the most promising strategy to achieve the near-zero-emission in transport and communication [58–60]. Ma et al. [61] predicted that the total demand of hydrogen of China is around 25.11 to 70.5376 million tons coal equivalent in 2050. Therefore, China has a great potential for developing hydrogen economy.

(3) Benefits for environmental protection

Environmental pollution, especially atmosphere pollution, has become a vital problem in China since more and more haze days are being observed in most Chinese cities along the eastcoast [62]. The only choice for China to solve this problem is to change its energy structure. Hydrogen is one of the most promising clean energy carriers in the future because it cannot only be used without pollutants, but also can be manufactured by using green processes, e.g. photolysis water splitting method, biological and photo-biological water splitting, thermal water splitting and biomass gasification [59,60,62]. Therefore, hydrogen is one of the most environment-friendly fuels that can, to some extent, solve the environmental problem of China.

- Weaknesses

High cost (W_1), lack of key technologies (W_2) and incompletion of hydrogen infrastructure (W_3) were investigated as the factors of weaknesses for the hydrogen economy in China.

(1) High cost

The cost of hydrogen energy has been discussed from a life cycle perspective including production, transport and storage, and use [63,64]. The cost for production, storage and transportation, and usage of 1 kg hydrogen in China was estimated to be about 6.82–12.16 Yuan RMB, 3.22–4.27 Yuan RMB, and 30.82–48.83 Yuan RMB, respectively (1 Yuan RMB = 0.16 US $) [64]. It can be seen that the cost in the use accounts for more than 70% of the total cost, which is the biggest obstacle that hinders the industrialization and commercialization of hydrogen fuel cell vehicles in China.

(2) Lack of key technologies

As a developing country, the development of hydrogen economy in China was relatively late, accordingly, the corresponding technologies for hydrogen production, storage and transport in China are not as advanced or mature as those in the developed countries [65]. The production of hydrogen in China was limited to the conventional processes, i.e. coal gasification, natural gas reforming and water electrolysis. China currently lacks the key technologies for hydrogen production using renewable resources, e.g. solar-powered and wind-powered hydrogen technologies; while these new emerging technologies are regarded as the promising pathways for hydrogen production in China due to their superior sustainability and the exceptional conditions of vast solar irradiation and high wind potential in China [32,59,66,67]. Meanwhile, there are significant challenges to developing hydrogen storage systems for storing large quantities of hydrogen for the commercialization in large scale, and more effort is required to accelerate the commercialization of high-pressure gaseous hydrogen storage technologies in China [68–70].

(3) Incomplete hydrogen infrastructure

Right now, one major obstacle for the advancement of hydrogen economy in China is the limited number of refueling stations due to the high cost of hydrogen infrastructure investment and the immature of its practical application.

- Opportunities

The factors regarded to be the opportunities of hydrogen economy in China consist of government support (O_1), high social acceptability (O_2) and deepened cooperation (O_3).

(1) Government support

The stakeholders in China including high-level governments and energy experts have showed increasingly interests and willingness on hydrogen economy, and vehicles using hydrogen fuel cells have been demonstrated at the Beijing Olympic Games, Shanghai World Expo, Guangzhou Asian Games and Shenzhen Universiade [71]. Many drafted policies, regulation and laws promoting the development of hydrogen economy in China have already taken effect. The Energy Saving Law, drafted in 1997, issued in 1998 and revised in 2007, is an essential national policy of China with the objective to promote energy saving, improve the energy utilization efficiency, protect the environment and achieve the harmonious development of economic and society. The Renewable Energy Law was approved by the Congress on February 28th, 2005, and took effect from January 1st, 2006, its stated aim is to optimize China's energy supply, mitigate environmental pollution, improve energy supply security, and promote rural social development [72]. The Economy Promotion Law, which was

adopted by the fourth session of the Standing Committee of the 11th National People's Congress on August 29th, 2008, and has been taken effect from January 1st, 2009, is closely correlated to the Renewable Energy Law with the aims to facilitate recycling, improve resource utilization efficiency, protect environment, and realize the sustainable development [52]. Moreover, a variety of policies for promoting the development of new and renewable energy were also issued by different implementation bodies. For instance, the 10th Five-year Plan on the industry of new and renewable energy was issued in 2001 by State Economy and Trade Commission of China. The National Development and Reform Commission issued the Provisional administrative measures on the price and expense allocation of electricity generated from renewable energy in 2006 [54]. All these policies, laws and regulation are beneficial for the development of hydrogen economy in China, demonstrating support for the hydrogen economy by the Chinese governments.

Meanwhile, a variety of technological programs concerning the production, storage, and use of hydrogen have been sponsored by the Chinese governments to promote the development of hydrogen economy in China since 2000 [56]. The Ministry of Science and Technology of China has launched several funding programs such as National Basic Research Programs (973 Programs) and High Technology Research and Development Program (863 Programs) for the research and development of hydrogen production, storage and utilization (e.g. fuel cell systems) in China [29].

(2) High social acceptability

With the booming of the Chinese economy, environmental contaminations caused by not only heavy industry but also transportation, especially atmospheric pollution, has become more and more severe [73,74]. For instance, the haze-fog problem in China which becomes more and more serious recently [75] drives China's administration to adjust China's energy structure. Hydrogen, as an efficient energy carrier, which cannot only be used with near-zero impacts on the environment during its oxidation, but also can reduce the risk of energy supply distribution and price volatility of the fossil energy markets, has great potential of high social acceptability in China with its advantages being known by more and more people, hydrogen economy would be approved and accepted by the public in China based on the survey in China and the experience learned from European case studies [76–78].

(3) Deepened cooperation

Hydrogen technologies in China are making great progress recently because of international and national cooperation. China is involving in international cooperation with the United States, the European Union, Canada, Italy and some other international organizations [79]. Domestically, Chinese companies, universities and research institutes have deepened their cooperation and established a number of production-education-research bases of hydrogen technology. For instance, Shanghai Fuel Cell Vehicles Powertrain Co., Ltd has cooperated with Tongji University in developing "Chaoyue" series of fuel cell cars [29].

- Threats

Deficiency of investment channels (T_1), competition with other renewable resources (T_2), and unconfirmed market potential (T_3) are regarded as threat factors.

(1) Deficiency of investment channels

At present, investments in hydrogen economy in China, including research and development, infrastructure construction, popularization of hydrogen applications, as well as the education on hydrogen technologies, are mainly sponsored by the governments or state-owned enterprises. Few private companies are likely to opt to invest in hydrogen industry due to its low profit and high risk, and the subsidies for hydrogen development from the government are prerequisite for many private hydrogen companies to sustain normal operation. For promoting the popularization and healthy development of hydrogen economy, the investments should be diversified in the future.

(2) Competition with other renewable resources

Although hydrogen shows a promising future in China, it is just an energy carrier rather than an energy source, and the competition with other renewable resources cannot be ignored. As an energy carrier, hydrogen has a similar role with electricity, which could also be manufactured from other renewable or low-carbon resources, e.g. wind, hydro, solar, nuclear and biomass [29]. Furthermore, the technologies for electricity generation from renewable resources are more advanced and mature than those for hydrogen production. For instance, the energy efficiencies of electricity produced from solar power and wind power are 13% and 39% (mean value), and the costs for electricity generated by the two pathways are 2.95 and 0.60 Yuan RMB/kW h (mean value), respectively [80,81]. In contrast, the energy efficiency of hydrogen production is still low, and therefore, the cost for hydrogen production is significantly high. Taking photovoltaic electrolysis and wind turbine electrolysis as examples, the energy efficiencies are only 5% and 31%, and the production costs are about 17.36 and 36.75 US$/day/kg, respectively [82,83]. Therefore, "hydrogen from renewables versus electricity from renewables" is still a debate in China, which, to some extent, has restricted the hydrogen application in large scale. Besides the drawbacks in technology and price, the environmental performance of hydrogen, especially when comparing

Table 1
SWOT matrix for hydrogen economy of China.

	Strengths (S)	Weaknesses (W)
	S_1: abundant resource reserves S_2: great development potential S_3: benefits for environmental protection	W_1: high cost W_2: lack of key technologies W_3: incomplete hydrogen infrastructure
Opportunities (O)	SO strategies.	WO strategies
O_1: government support	SO_1: developing large scale coal-hydrogen technologies with CCS	WO_1: government subsidies and tax allowance
O_2: high social acceptability	SO_2: popularizing fuel cell vehicles	WO_2: foreign capital importation
O_3: deepened cooperation	SO_3: establishing hydrogen market and industry standards	
Threats (T)	ST strategies	WT strategies
T_1: deficiency of investment channel	ST_1: encouraging private participation of Industrialization and Commercialization of hydrogen energy	WT_1: developing new and sustainable hydrogen technologies
T_2: competition with other renewable resources	ST_2: establishing hydrogen development priority strategy in China	WT_2: improving hydrogen infrastructure
T_3: unconfirmed market potential		

with other energy carrier (i.e. electricity) produced by renewable energy resources in life cycle perspective, is also questionable as the environmental performance of hydrogen production by different pathways is quite different.

(3) Unconfirmed market potential
The future of hydrogen economy in China, especially fuel cell vehicles, faces some unpredictable risks in market development. The main risk is the unconfirmed potential market. As mentioned, hydrogen, as a clean energy carrier, has the high risk to be partly substituted by electricity, e.g. wind-electricity, hydro-electricity, solar-electricity and nuclear-electricity. Therefore, the unconfirmed potential market is a threat for the development of hydrogen economy in China.
Step 5—Strategy recommendations.
According to the SWOT analysis of the hydrogen economy in China, a portfolio of strategies were obtained by matching the internal indicators including 'Strengths' and 'Weaknesses' with the external indicators including 'Opportunities' and 'Threats'. As presented in Table 1, nine recommended strategies have been obtained.

- *SO* strategies
  SO_1: Developing coal-hydrogen technologies in large scale with the function of CO_2 capture and storage (CCS)—fully taking the advantages of coal richness in China and minimizing the negative environmental impacts.
  SO_2: Popularizing fuel cell vehicles—increasing the consumption of hydrogen by popularizing hydrogen fuel cell vehicles and limiting fossil fuel based vehicles.
  SO_3: Establishing hydrogen market and industry standards—standardizing the hydrogen market and hydrogen industry to guarantee the healthy and harmonious development of hydrogen economy.
- *WO* strategies
  WO_1: Government subsidies and tax allowance—mitigating the financial burden of the hydrogen investors by giving the benefits of subsidies and tax allowance.
  WO_2: Foreign capital importation—developing free market mechanism and attracting new hydrogen technologies.
- *ST* strategies
  ST_1: Encouraging the participation of private capitals in the industrialization and commercialization of hydrogen energy—breaking the monopoly of state-owned enterprises and encouraging innovation.
  ST_2: Establishing hydrogen development prior strategy in China—determining the strategic priority of hydrogen among all the alternative energy sources for substituting fossil fuels by the non-fossil fuels.
- *WT* strategies
  WT_1: Developing new and sustainable hydrogen technologies—enhancing the advancement of hydrogen technologies.
  WT_2: Improving hydrogen infrastructure—investing more in infrastructure to promote hydrogen economy.

All these strategies are identified as helpful for promoting the development of hydrogen economy in China, and their effects on stimulating hydrogen economy of China are unclear. Thus, it is difficult for the stakeholders/decision-makers to correctly draw the roadmap of the hydrogen economy, and thus, to make appropriate budget planning and resources allocation without raking the priorities of these strategies. Therefore, it is meaningful to prioritize the importance of these strategies. The method for prioritizing and ranking the importance of these strategies is presented in Section 3.

3. Strategy prioritization

The prioritization of the strategies is based on their effects on exerting the factors in strengths, mitigating the factors in weaknesses, exploiting the factors in opportunities and avoiding the factors in threats. Consequently, the prioritization of the strategies concerns multiple criteria, and therefore, it is a typical multi-criteria decision-making (MCDM) problem, which should be addressed by using a MCDM method.

There are various MCDM methods in the literatures, i.e. Analytic Hierarchy Process [82], Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [84], Data envelopment analysis (DEA) [84,85] goal programming (GP) [86], Preference Ranking Organization Method for Enrichment Evaluation (PROTHEE), and Elimination and Choice Translating Reality (ELECTRE) [87], and their modified and hybrid methods, e.g. fuzzy AHP [88,89], AHP/DEA integrated approach [90,91] and fuzzy Delphi method [92]. Among these methods, GP is the most suitable one for prioritizing the strategies for promoting the hydrogen economy in China. Since the strategies prioritization has to consider the expectations and goals of the stakeholders/decision-makers as well as the weights of the decision criteria, the goals and weights regarding each decision criterion are allowed to be set by the stakeholders/decision-makers in GP method. Moreover, by using the GP method, the best alternative could be determined by establishing a mixed 0–1 integer linear programming to minimize the total weighted deviations to all the goals [93].

The traditional GP method can only address the MCDM problems with crisp numbers. While it is difficult for the stakeholder/decision-makers to directly use crisp numbers to assign the weights of the decision criteria and assess the effect of each strategy, its convenient for them to directly use linguistic variables such as "very high" and "significantly high" to weigh the importance (weights) of the decision criteria, and use linguistic variables such as "Good" and "Bad" to depict the performance of each strategy. In this study, a novel MCDM method by integrating GP and fuzzy theory has been developed for prioritizing the strategies for promoting hydrogen economy of China, in which, the fuzzy theory was used as a bridge to link the linguistic variables and

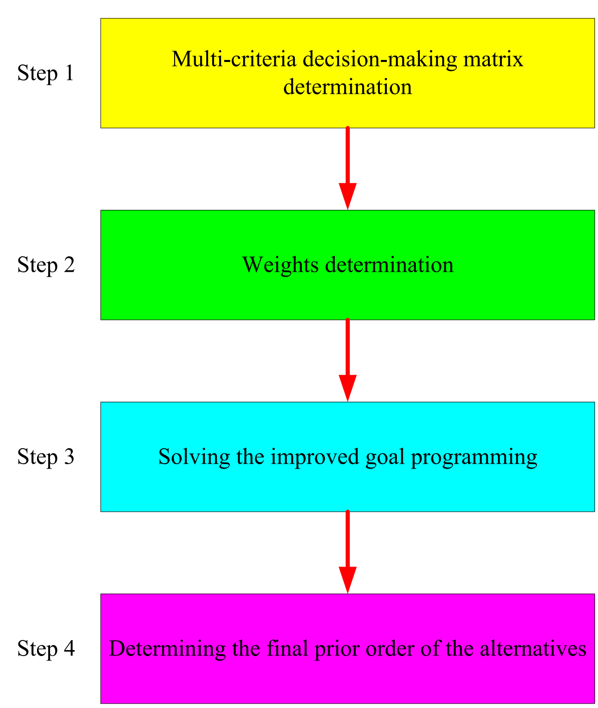

Fig. 4. The framework of MCDM methodology.

crisp numbers by membership functions of the linguistic variables [93,94–97].

3.1. Fuzzy goal programming of the MCDM method

The principle of goal programming is to select the best alternative that can satisfy the goals or targets set by the decision-makers, unfortunately, it is impossible for any alternative to satisfy all the goals. Therefore, minimizing the non-achievement of the corresponding goals under certain soft and hard constraints can be used to select the alternative that can satisfy the goals as much as possible.

The proposed MCDM method (Fig. 4) can be divided into four steps including multi-criteria decision-making matrix determination, weights determination, solving the goal programming, and determining the final prior order of the alternatives.

Step 1: Multi-criteria decision-making matrix determination. The decision making matrix consists the alternatives, the criteria, and the goals of the decision-makers/stakeholders with respect to the criteria, as showed in Eq. (1).

$$X = \begin{array}{cccccc} & C_1 & C_2 & \cdots & C_n \\ A_1 & x_{11} & x_{12} & \cdots & x_{1n} \\ A_2 & x_{21} & x_{22} & \vdots & x_{2n} \\ \vdots & \vdots & \cdots & \ddots & \vdots \\ A_m & x_{m1} & x_{m2} & \cdots & x_{mn} \\ T & g_1 & g_2 & \cdots & g_n \end{array} \tag{1}$$

where A_i represents the ith alternative, C_j represents the jth criterion, x_{ij} represents the value of the jth criterion of the ith alternative, T is a vector of the goals and g_j represents the jth goal set by the decision-makers/stakeholders.

In this step, stakeholders/decision-makers are invited to use the linguistic variables (Table 2) to depict the performances of the alternatives regarding each criterion, and the linguistic variables were then transformed into triangular fuzzy numbers according to Table 2. Subsequently, the triangular fuzzy numbers ($\tilde{x}_{ij} = \left(x_{ij}^L, x_{ij}^M, x_{ij}^U\right)$) for describing the performance of the ith alternative regarding the jth criterion, were transformed into crisp numbers by CoG method (Eq. (2)) [98]. For instance, if an alternative with respect to a criterion is regarded as good (GD) and the corresponding triangular fuzzy number was determined to be (5, 7, 9), the fuzzy number could be transformed into a crisp number of 7 ($5+2 \times 7+9/4=7$). Similarly, the goal representing the expectation of the stakeholders/decision-makers on each criterion could also been determined.

$$x_{ij} = \frac{\tilde{x}_{ij}^L + 2\tilde{x}_{ij}^M + \tilde{x}_{ij}^U}{4} \tag{2}$$

where x_{ij} and $\tilde{x}_{ij}$ are the crisp numbers and the triangular fuzzy numbers describing the performance of the ith alternative regarding the jth criterion, respectively. $\tilde{x}_{ij}^L$, $\tilde{x}_{ij}^M$ and $\tilde{x}_{ij}^U$ represent the three elements in the fuzzy number$\tilde{x}_{ij}$.

Table 2
The linguistic variables for assessing the performance of alternatives with respect to each criterion.

Linguistic variables	Abbreviation	Fuzzy number
Worst	WT	(0,1,1)
Worse	WE	(1,1,3)
Bad	BD	(1,3,5)
Medium	MM	(3,5,7)
Good	GD	(5,7,9)
Better	BR	(7,9,9)
Best	BT	(9,10,10)

Table 3
The linguistic variables for determining the importance of the criteria.

Linguistic variables	Abbreviation	Fuzzy number
Significantly low	SL	(0, 0.1, 0.2)
Very very low	VVL	(0.1, 0.2, 0.3)
Very low	VL	(0.2, 0.3, 0.4)
Low	L	(0.3, 0.4, 0.5)
Medium	M	(0.4, 0.5, 0.6)
High	H	(0.5, 0.6, 0.7)
Very high	VH	(0.6, 0.7, 0.8)
Very very high	VVH	(0.7, 0.8, 0.9)
Significantly high	SH	(0.8, 0.9, 1.0)

Step 2: Weights determination.

In this study, nine linguistic terms, i.e. significantly low (SL), very very low (VVL), very low (VL), low (L), medium (M), high (H), very high (VH), very very high (VVH) and significantly high (SH) are used for depicting the importance of the criteria. The linguistic terms can be transformed into triangular fuzzy numbers according to the corresponding membership functions (Table 3) Meanwhile, the triangular fuzzy numbers ($\tilde{\omega}_j = \left(\tilde{\omega}_j^L, \tilde{\omega}_j^M, \tilde{\omega}_j^U\right)$ for describing the weight of the jth criterion, could be transformed into crisp numbers by the mean area method [98] (Eq.(3)). For instance, if the importance of a criterion is regarded as significantly low (SL), so the triangular fuzzy number is (0, 0.1, 0.2), and the fuzzy number could be transformed in to a crisp number of 0.1 ($0+2 \times 0.1+0.2/4=0.1$). Subsequently, the weights could be normalized according to Eq. (4).

$$\omega_j' = \frac{\tilde{\omega}_j^L + 2\tilde{\omega}_j^M + \tilde{\omega}_j^U}{4} \tag{3}$$

where ω_j' represents the weight of the ith criterion described by using a crisp number.

$$\omega_j = \frac{\omega_j'}{\sum_{j=1}^{n} \omega_j'} \tag{4}$$

where ω_j represents the normalized weight of the ith criterion described by a crisp number.

Step 3: Solving the goal programming.

The methodology to select the best alternative by using the goal programming was shown in the developed mixed integer linear programming. The objective function is to minimize the total weighted deviations, and the goal constraints represent the relationship between the deviation variables and the goals, 0–1 constraint represents the decision variable, selection constraint denotes that only one alternative could be selected as the best. The idea of this method is to determine the alternative that can satisfy the goal of the stakeholders/decision-makers towards each criterion as much as possible.

Objective

$$\text{Min} \sum_{j=1}^{n} \omega_j (d_j^+ + d_j^-) \tag{5}$$

Goal constraints

$$\sum_{i=1}^{m} x_{ij} z_i - d_j^+ + d_j^- = g_j \, j = 1, 2, \cdots, n \tag{6}$$

where x_{ij} is the value of the jth criterion in the ith alternative, z_i represents the decision variable. d_j^+ and d_j^- represent the over- and under-achievement of the jth goal, respectively.

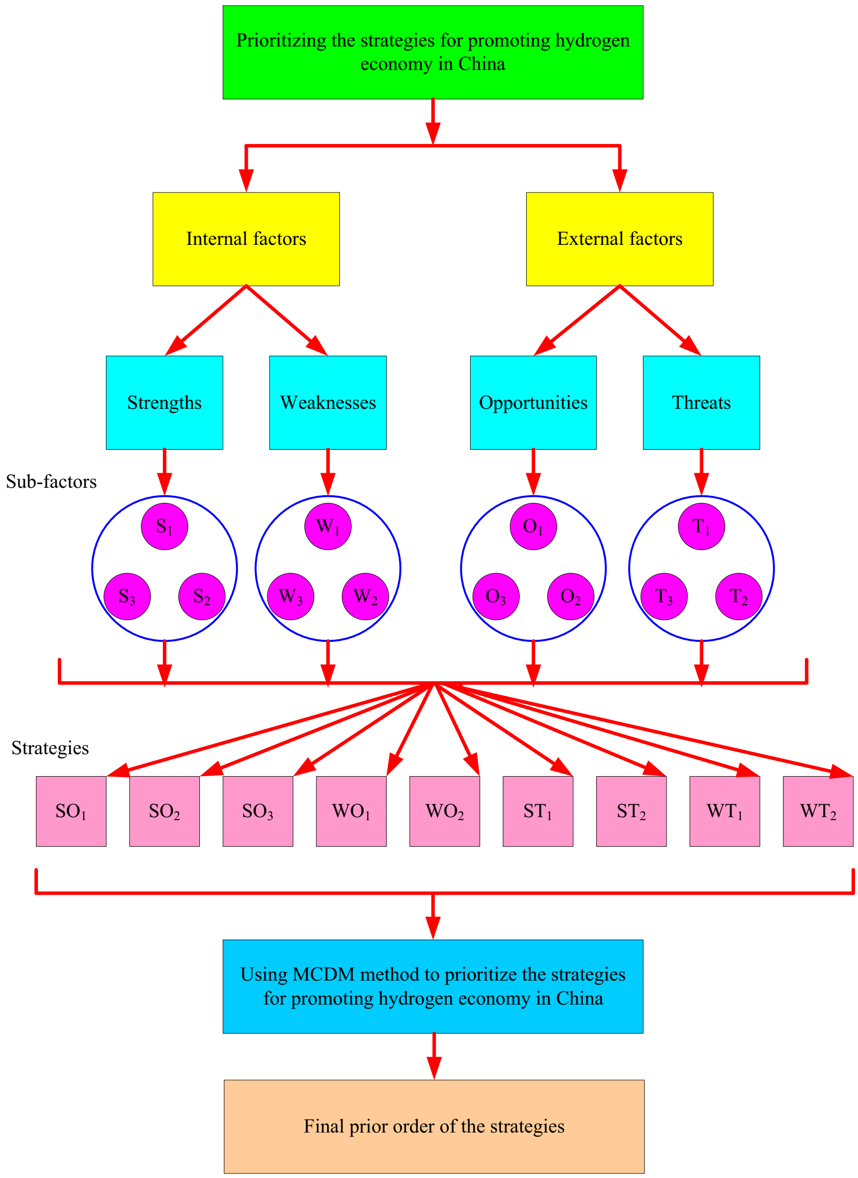

Fig. 5. Framework for prioritizing the strategies.

Table 4
Multi-criteria decision-making matrix using linguistic variables.

	S_1	S_2	S_3	W_1	W_2	W_3	O_1	O_2	O_3	T_1	T_2	T_3
SO_1	BR	BR	BT	GD	MM	BD	BT	MM	BR	GD	BT	0
SO_2	BT	BT	BT	0	WT	GD	GD	MM	GD	BR	BT	BT
SO_3	GD	GD	0	0	0	BD	MM	MM	MM	BR	BT	BT
WO_1	BT	GD	BT	BT	BD	BR	BT	BT	0	BR	BT	MM
WO_2	BR	BD	0	BR	BT	MM	MM	BD	BT	BT	GD	0
ST_1	GD	MM	0	MM	MM	GD	BD	BR	GD	BT	GD	WE
ST_2	BT	BT	BT	GD	GD	BR	BT	BT	GD	MM	BT	GD
WT_1	BT	BR	BT	BR	BT	BD	GD	BT	BT	BD	BT	BD
WT_2	GD	MM	BD	0	0	BT	BD	BR	WE	BD	BT	MM
T	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT

0–1 Constraint

$$z_i = \begin{cases} 1\text{, ifthe}j\text{thalternativehasbeenselected} \\ 0\text{, otherwise} \end{cases} \tag{7}$$

Selection constraint

$$\sum_{i=1}^{m} z_i = 1 \tag{8}$$

Table 5
Multi-criteria decision-making matrix described by using crisp numbers.

	S_1	S_2	S_3	W_1	W_2	W_3	O_1	O_2	O_3	T_1	T_2	T_3
SO_1	8.5	8.5	9.75	7	5	3	9.75	5	8.5	7	9.75	0
SO_2	9.75	9.75	9.75	0	0.75	7	7	5	7	8.5	9.75	9.75
SO_3	7	7	0	0	0	3	5	5	5	8.5	9.75	9.75
WO_1	9.75	7	9.75	9.75	3	8.5	9.75	9.75	0	8.5	9.75	5
WO_2	8.5	3	0	8.5	9.75	5	5	3	9.75	9.75	7	0
ST_1	7	5	0	5	5	7	3	8.5	7	9.75	7	1.5
ST_2	9.75	9.75	9.75	7	7	8.5	9.75	9.75	7	5	9.75	7
WT_1	9.75	8.5	9.75	8.5	9.75	3	7	9.75	9.75	3	9.75	3
WT_2	7	5	3	0	0	9.75	3	8.5	1.5	3	9.75	5
T	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75

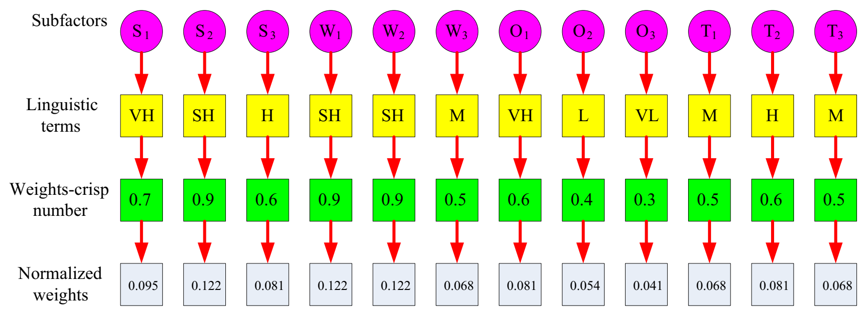

Fig. 6. The weights of the sub-factors.

Table 6
The results of the mixed-integer linear programming.

Item	z_7	$z_i(i=1,2,\ldots,9 \cap i \neq 7)$	Objective function
Value	1	0	1.37875

Step 4: Determining the final prior order of the alternatives. In this step, the second-best alternative is first determined by eliminating the best alternative and repeating Step 3. Subsequently, the third-best, the fourth-best,…,and the mth best alternative can be determined by eliminating the alternatives that have already been ranked and repeating Step 3. Consequently, the prior order of the alternatives can be ranked.

3.2. Results and discussion

As showed in Fig. 5, the proposed MCDM method was used to prioritize the strategies for promoting the hydrogen economy in China, which was obtained by the SWOT analysis. The procedures were specified as follows.

Step 1—Multi-criteria decision-making matrix determination. The multi-criteria decision-making matrix was determined in the colloquium, the coordinator first provided a multi-criteria decision-making matrix, then the experts were asked to modify it using the linguistic variables (Table 2) to assess the effect of these strategies on taking advantages of the sub-factors in strengths (S), mitigating the sub-factors in weaknesses (W), exploiting the sub-factors in opportunities (O) and avoiding the sub-factors in threats (T) based on the current status of hydrogen economy in China and their own experience. At the end of the meeting, a final consensus with respect to each element in the matrix was achieved via discussions. It is noteworthy that the effect of a strategy on a sub-factor could be denoted by zero if the strategy is useless to that sub-factor. The final results determined by the experts were presented in Table 4, Then, the linguistic variables were transformed into crisp numbers according to Eq.(2) and the results were presented in Table 5.

Step 2—Weights determination. Fuzzy method is used to determine the weights of sub-factors regarding strengths, weaknesses, opportunities and threats, respectively. The aim of this step is to evaluate the importance of the factors that affect the development of hydrogen economy in China. The experts were asked to use the linguistic variables in Table 3 to weigh the importance of the sub-factors. Then, the linguistic variables were transformed into crisp numbers according to Eq. (3). Subsequently, the normalized weights of the sub-factors were calculated and the results were presented in Fig. 6.

Step 3—Solving the goal programming.

In this steps. the nine strategies (SO_1, SO_2, SO_3, WO_1, WO_2, ST_1, ST_2, WT_1, WT_2) are labeled as the ith ($i=1, 2, 3, 4, 5, 6, 7, 8, 9$) strategy, respectively. Then, the mixed-integer linear programming for selecting the most effective and important strategy was formulated as follows.

Objective function

$$\text{Min } \sum_{j=1}^{n} \omega_j (d_j^+ + d_j^-) \tag{9}$$

Constraints

$$XZ - D^+ + D^- = T \tag{10}$$

$$\sum_{i=1}^{9} z_i = 1 \tag{11}$$

$$z_i \in \{0, 1\}, i = 1, 2, \cdots, 9 \tag{12}$$

$$W = [\omega_1, \omega_2, \cdots, \omega_n] = [0.095, 0.122, 0.081, 0.122, 0.122, 0.068, 0.081, 0.054, 0.041, 0.068, 0.081, 0.068] \tag{13}$$

$X = |$ 8.58.59.757539.7558.579.750

9.759.759.7500.7577578.59.759.75
7700035558.59.759.75
9.7579.759.7538.59.759.7508.59.755
8.5308.59.755539.759.7570
75055738.579.7571.5
9.759.759.75778.59.759.75759.757
9.758.59.758.59.75379.759.7539.753
753009.7538.51.539.755| (14)

$$Z=[z_1,z_2\cdots,z_9] \tag{15}$$

$$\{D^+,D^-,T\}=\left|\begin{array}{ccc} d_1^+ & d_1^- & 9.75 \\ d_2^+ & d_2^- & 9.75 \\ d_3^+ & d_3^- & 9.75 \\ d_4^+ & d_4^- & 9.75 \\ d_5^+ & d_5^- & 9.75 \\ d_6^+ & d_6^- & 9.75 \\ d_7^+ & d_7^- & 9.75 \\ d_8^+ & d_8^- & 9.75 \\ d_9^+ & d_9^- & 9.75 \end{array}\right| \tag{16}$$

where X is the processed multi-criteria decision-making matrix, Z is the vector of decision variables, D^+ and D^- are the over- and under-achievement vectors of the goals, respectively, T is the vector of the goals, $z_i=1$ indicates that the ith strategy was selected as the most effective and important strategy, otherwise, it was not be selected as the most effective and important strategy.

The programming was coded in LINGO 11.0, and the results were presented in Table 6. The results show that the seventh strategy, namely $ST2$ (establishing the prior strategic level of hydrogen energy in China), is regarded as the most effective and important strategy for stimulating the development of hydrogen economy in China.

Step 4—Determining the final prior order of the strategies. By eliminating the strategies that have already been ranked, the second best, the third best, and until the last best strategy were determined by repeating step 3. The final prior order of the strategies was determined to be $ST_2>WT_1>WO_1>SO_1>SO_2>$-$WO_2>ST_1>SO_3>WT_2$. Accordingly, the strategy of establishing hydrogen development priority strategy in China is recognized as the most effective and important factor for simulating the development of hydrogen economy in China, which is followed by developing new and sustainable hydrogen technologies, government subsidies and tax allowance, developing large scale of coal-hydrogen technologies with carbon dioxide capture and storage, popularizing fuel cell vehicles, foreign capital importation, encouraging private participation of industrialization and commercialization of hydrogen energy, establishing hydrogen market and industry standards, and perfect hydrogen infrastructure.

It is reasonable that the strategy "establishing hydrogen development prior strategy in China", which belongs to the *ST* strategies and can make hydrogen the top priority for substituting fossil fuels, was recognized as the most effective and important strategy for promoting the hydrogen economy of China because it is beneficial for taking advantages of the strengths, mitigating the weaknesses, exploiting the opportunities and avoiding the threats. For instance, it is helpful to promote the use of abundant resources such as biomass and hydropower for hydrogen production, the development of key technologies, the improvement of hydrogen infrastructure, and the international cooperation. Moreover, this strategy reflects that the hydrogen industry in China needs clear and positive support from the Government. It has been pointed out that Chinese government hesitated to develop hydrogen energy due to the conflicts of the experts' options [99]. This statement is consistent to the perspectives reported in two literature sources [29,100]. Lu et al. [29] argued that government incentive is an effective way to encourage the popularization of renewable energies, which is likely to play an important role in China's hydrogen industry. Pudukudy [100] stated that government's incentive and public policies are key factors for the development of hydrogen economy in China.

More specifically, there are several main reasons that "establishing hydrogen development prior strategy" is regarded as the most important strategies for promoting hydrogen economy in China. (i) China's energy structure is coal-based, and the low lost to deliver the "dirty" energies and establish the infrastructures of the coal power hinders the development of hydrogen economy [29]. It is beneficial to popularize the hydrogen industry in large scale by establishing the strategic priority of hydrogen as alternative energy carrier; (ii) "establishing hydrogen development prior strategy" can stimulate the public perception of hydrogen fuel cell vehicles as a new emerging transport pattern, and then improve the acceptance of the fuel cell vehicles by the public; (iii) "establishing hydrogen development prior strategy" can improve the competiveness of hydrogen with other energy carriers, especially electricity; (iv) "establishing hydrogen development prior strategy" is beneficial to get financial support from the government to establish the infrastructure, which is the major barrier for the commercialization of hydrogen.

Developing new and sustainable hydrogen technologies (belonging to *WT* strategies) was ranked as the second most effective and important strategy. The reason why this strategy is so important is that the implementation of this strategy can improve energy conversion efficiency in hydrogen production, exploit the renewable resources as much as possible, extend hydrogen market, reduce the cost of hydrogen production, enhance the advancement of hydrogen technologies and improve the competitiveness of hydrogen comparing to other renewable energies.

Government subsidies and tax allowance (belonging to *WO* STRATEGIES) was ranked as the third important strategy. Government subsidies and tax allowance is the most effective way to solve the problem of the high cost of hydrogen power and enhance the competitiveness of hydrogen compared to some other renewable energies.

Developing large scale coal-hydrogen technologies with carbon dioxide capture and storage function was ranked fourth. The main effect of implementing this strategy would be to reduce the cost of hydrogen, enhance the competitiveness of hydrogen compared to other renewable energies, and benefit the environmental protection by carbon dioxide capture and storage. Compared to other pathways, the cost of hydrogen manufactured from coal is relatively low in China, and coal-based hydrogen technologies are suitable for hydrogen development in large scale. Simbech [101] pointed out that CO_2 capture and storage is the essential bridge to the hydrogen economy, which is especially feasible for the development of hydrogen economy in China as it cannot only fully use abundant coal resource in China, but also solve the serious greenhouse effect caused by using coal for hydrogen production.

Popularizing fuel cell vehicles was ranked at the fifth place, which is the most significant driving force of hydrogen market as the market will adversely affect the upstream stages of hydrogen economy. In other words, popularizing fuel cell vehicles aims at enlarging hydrogen demand in China, and further to create market pull.

4. Conclusion

Hydrogen economy has great potential for enhancing China's energy security and mitigating the emission of greenhouse gases. In order to help the stakeholders/decision-makers to understand the current status of hydrogen economy in China, and then draft

effective future strategies to promote the development of hydrogen economy in China, SWOT analysis has been used to analyze the current status of hydrogen economy in China and nine effective strategies were proposed. In addition, a multi-criteria decision-making method by combining the goal programming and fuzzy theory was developed for prioritizing the strategies form the most effective and important to the least.

In the SWOT analysis, twelve sub-factors, i.e. abundant resource reserves, great development potential, and benefits for environmental protection (belonging to 'Strengths'), high cost, lack of key technologies, and incompletion of hydrogen infrastructure (belonging to 'Weaknesses'), government support, high social acceptability, and deepened cooperation (belonging to 'Opportunities'), deficiency of investment channels, competition with other renewable resources and unconfirmed potential market (belonging to 'Threats'), were identified to depict the current status of hydrogen economy in China. Four types of strategies (*SO* strategies, *WO* strategies, *ST* strategies and *WT* strategies) have been obtained, with *SO* strategies consisting of developing large scale of coal-hydrogen technologies with carbon dioxide capture and storage, popularizing fuel cell vehicles, and establishing hydrogen market and industry standards, *WO* strategies comprising government subsidies and tax allowance, and foreign capital importation, *ST* strategies including encouraging private participation of industrialization and commercialization of hydrogen energy, and establishing hydrogen development priority strategy in China, and *WT* strategies consisting of developing new and sustainable hydrogen technologies, and perfecting hydrogen infrastructure.

The developed MCDM method by combining goal programming and fuzzy theory was used to prioritize the strategies for roadmap design of hydrogen economy, appropriate budget planning and resource allocation to promote the hydrogen economy in China. In the method, stakeholders/decision-makers are allowed to use linguistic terms to assess the effect of each strategy, and goals can be set to select the strategy that can satisfy the expectation of the stakeholders/decision-makers as much as possible. The prior sequence of the strategies from the most effective and important to the least was determined to be: establishing hydrogen development prior strategy, developing new and sustainable hydrogen technologies, government subsidies and tax allowance, developing large scale of coal-hydrogen technologies with carbon dioxide capture and storage, popularizing fuel cell vehicles, foreign capital importation, encouraging private participation of industrialization and commercialization of hydrogen energy, establishing hydrogen market and industry standards, and perfecting hydrogen infrastructure. According to the prior sequence, stakeholders/decision-makers can draft the future actions towards a better future of hydrogen economy in China.

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Appendix A. Questionnaire for SWOT analysis of hydrogen economy in China

Questionnaire for SWOT analysis of hydrogen economy in China

Name:___ Occupation____

Dear Sir/Madam,

Thank you very much for your participation in the following questionnaire, this questionnaire does not concern any of your privacies the results will only be used for academic research. You just need to answer the questions based on your own experience and the supplementary materials. Please return the questionnaire to renjingzheng123321@163.com or lcdong72@cqu.edu.cn. Thank you for your assistance!

Question 1. What are the advantages for developing hydrogen economy in China?

i. Why China is suitable for the development of hydrogen economy?
ii. What are the benefits of the development of hydrogen economy in China?
iii. What are the key factors that can drive China to be a competitive hydrogen market?

Question 2. What are the weaknesses for the development of hydrogen economy in China?

i. What could be improved for a better hydrogen economy in China?
ii. What are not done properly in the current hydrogen economy of China?
iii. What should or could be avoided in the current hydrogen economy of China?
iv. What are the obstacles that prevent the progress of the hydrogen economy in China?
v. Where are the complaints in the hydrogen economy of China coming from?

Question 3. What are the opportunities that could be exploited for promoting the development of hydrogen economy in China?

i. Where are the good chances facing hydrogen economy in China?
ii. What are the policies and legislations drawn by the Government that are beneficial for hydrogen economy in China?
iii. What benefits may occur with the development of hydrogen economy in China?

Question 4. What are the threats that may be faced in hydrogen economy of China?

i. What are the severe problems that exist in hydrogen economy of China?
ii. Are the required support and necessary facilities for the development of hydrogen economy in China available?
iii. Are the new emerging technologies threatening the development of hydrogen economy in China?
iv. Do the stakeholders in China show their interests and willingness to support the development of hydrogen economy?

Question 5. Do you have some other suggestions about the strengths, weaknesses, opportunities, and threats of hydrogen economy in China?

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.09.014.

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